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14. ABSTRACT The results of a comprehensive study of optical interactions with frequency-selective recording materials are reported along with ancillary results related to high-speed tuning and reference-free stabilization of associated lasers. Frequency-selective recording materials provide the physical basis for time-space or 4D holography wherein the full spatial and temporal information contained in an optical signal can be stored and/or processed. It is shown that 4D holographic recall signals can be substantially stronger than previously believed possible. Innovative external-cavity diode laser designs supportive of very high-speed laser tuning and dynamic stabilization are also reported. Preliminary work on the use of composite grating devices to emulate the functionality normally associated with frequency-selective materials is also presented. Composite grating devices provide a basis for robust optical signal processing operative over extensive ranges of bandwidths and are entirely free of the constraints normally associated with intrinsically frequency-selective materials.					
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Executive Summary

In viewing a holographic image, one experiences the same qualities of depth and perspective associated with direct viewing of an object. These image attributes follow from the holographic recording method wherein interference with a reference beam is utilized to effect recording of the entire wavefront of a image-carrying beam. The recording material need only capture the reference beam - image beam interference pattern over a two-dimensional planar region and thus need only possess spatially-selective optical response. Some materials, such as rare-earth-ion-doped crystals, possess not only a spatially selective response capability, but also a spectrally selective response. Such materials can differentially respond to the various spectral components within an optical signal field. Frequency-selective materials open the door to a range of exciting capabilities centered around the temporal analog to holographic recording. Frequency-selective materials provide for the recording of "spectral wavefronts" of optical signal beams. By exposing a frequency-selective recording material to reference and signal beams, both exhibiting appropriate time dependence, one can record the Fourier spectrum and hence all temporal information carried by the signal beam. Material properties set maximum time durations that can be resolved. Analogously to spatial holography, temporal images can be recalled by re-exposing the spectral hologram to the reference beam to stimulate a replaying of the stored, time-dependent optical signal. In other situations, output signals representing the convolution or cross correlation of two input optical signals can be created. This ability provides the basis of high speed optical signal processing. Process utility is universally enhanced through development of implementational methods effective to maximize output signal strength in an absolute and fractional sense relative to inputs. In the course of the present work, conditions on materials and input optical signals have been identified that lead to almost two orders of magnitude larger spectral holographic output signals than had previously been considered possible. In the case of optical signal regeneration, output signals having intensities even larger than those of input signals have been shown possible through theory and experiment. In order to produce efficient spectral holographic signals, the storage material must have high effective optical thickness - either single pass or through multi-pass cavity effects. Also, the reference beam must provide spectrally uniform excitation

and be sufficiently intense. Related results obtained in the present work consist of the realization of an external cavity diode laser design that provides high coherence combined with the ability to tune at Gigahertz/nanosecond rates. Another laser related result, embodied in a patent submission now pending issue, is the development of a fiber-based laser frequency stabilization method. This method is unique in that no fixed frequency reference is used in the stabilization procedure. Rather, the laser is locked or spectrally tuned by controlling the time rate of change of the frequency. The latter quantity is determined by monitoring the beat between direct laser output with a fiber-delayed (earlier time) laser output. The referenceless aspect of the locking method is unique and very useful in situations where laser output must be extremely frequency agile while at the same time being maximally stable. Yet another aspect of the work completed involves the mapping of spectral holographic function onto materials that have no intrinsic frequency sensitivity and thus free of the low temperature constraints typical of such materials. In this vein, the concept of a composite grating has been invented. Composite grating devices are comprised of an array of simple gratings (sometimes spatially overlapped on a surface or within a volume) each of which controls the diffraction of a specific sub-bandwidth of light from an input direction to an output direction. In this way, they are direct analogous of devices based on frequency-selective materials wherein sub-bandwidths of light are controlled by different subgroups of absorbers. The primary difference between composite grating devices and devices based on frequency-selective materials is that in the former sub-bandwidth size is controlled by device size while in the latter it is controlled by intrinsic material spectral selectivity. By appropriate overlay of simple gratings quite general spectral transfer functions can be obtained. Composite grating devices provide for optical signal processing at a wide range of signal bandwidths, optical layer intelligence in optical communication systems, and pulse-shape storage in both static and dynamic environments. At the same time, composite grating devices are robust physically and environmentally and can be implemented in fibers or integrated waveguide devices. Composite grating devices may be a vital key to the integration of intelligence into the physical layer of optical communication systems.

Supported Journal Publications

1. "Polarization-dependent Rabi frequency beats in the coherent response of Tm(3+) in YAG," Greiner, C., Boggs, B., Loftus, T., Wang, T. and Mossberg, T. W., Physical Review A (Rapid Communications) **60**, R2657-60 (1999).
2. "Experimental study of photon-echo size in optically thick media," Wang, T., Greiner, C., Bochinski, J. R. and Mossberg, T. W., Physical Review A (Rapid Communications) **60**, R757-60 (1999).
3. "Optical waveform processing and routing with structured surface gratings," Babbitt, W. R., and Mossberg, T. W., Opt. Commun. **148**, 23 (1998).
4. "Simple high-coherence rapidly tunable external-cavity diode laser," Boggs, B., Greiner, C., Wang, T., Lin H. and Mossberg, T. W., Optics Lett. **23**, 1906-8 (1998).
5. "Experimental observation of photon echoes and power-efficiency analysis in a cavity environment," Wang, T., Greiner, C., Mossberg, T.W., Optics Lett. **23**, 1736-8 (1998).
6. "Laser frequency stabilization by means of optical self-heterodyne beat-frequency control," Greiner, C., Boggs, B., Wang, T. and Mossberg, T. W., Optics Lett. **23**, 1280-2 (1998).
7. "Photon echo signals: beyond unit efficiency," Wang, T., Greiner, C., Mossberg, T. W., Optics Commun. **153**, 309-13 (1998).
8. "Single-sideband spectral holographic optical memory," Lin, H., Wang, T. and Mossberg, T. W., Opt. Lett. **21**, 1866 (1996).

Conference Contributions

1. "Observation of polarization-dependent Rabi frequency beats in optical nutation signals in Tm3+:YAG"; Greiner, C., Boggs, B., Loftus, T., Wang, T. and Mossberg T. W.; Presentation at the 1999 Annual Meeting of the Optical Society of America, session code WLL 167.
2. "Experimental observation of efficient photon echo in optically thick media;" Wang, T., Greiner, C., Bochinski, J. R. and Mossberg T. W.; Presentation at the 1998 Annual Meeting of the Optical Society of America, session code TuQ5.

3. "Laser frequency stabilization by means of optical self-heterodyne beat-frequency control;" Greiner, C.; Boggs, B.; Wang, T.; Mossberg, T.W.; Technical Digest. Summaries of Papers presented at the Conference on Lasers and Electro-Optics. Conference Edition, 1998 Technical Digest Series, Vol.6 (IEEE Cat. No.98CH36178).
4. "Cavity enhancement of coherent transient signals;" Wang, T., Greiner, C. and Mossberg, T. W.; Presentation at the 1997 Annual Meeting of the Optical Society of America, session code ThKK4.
5. "Experimental demonstration of temporal-waveform-controlled spatial routing of optical beams via spatial-spectral filtering," Wang, T., Lin H. and T. W. Mossberg, CLEO '96, Summaries of papers presented at the Conference on Lasers and Electro-Optics, Vol.9. 1996 Technical Digest Series, Conference Edition (IEEE Cat. No.96CH35899), p. 544, 349-50.
6. Wang, T., Lin H. and Mossberg, T. W., "Single sideband data retrieval using swept-carrier optical memory," CLEO '96. Summaries of Papers Presented at the Conference on Lasers and Electro-Optics, Vol.9, 1996 Technical Digest Series. Conference Edition (IEEE Cat. No.96CH35899), p. 544, 196-7.
7. "Spectral memory & other applications of spatial-spectral holography," Mossberg, T. W., Conference Proceedings. LEOS '96 9th Annual Meeting. IEEE Lasers and Electro-Optics Society 1996 Annual Meeting (Cat. No.96CH35895).
8. "Spectral holographic optical data storage," Mossberg, T. W., Presentation at the 1996 Annual Meeting of the Optical Society of America, session code MX3.
9. "Optical heterodyne study of frequency-swept, external cavity, diode laser coherence properties," Wang, T., Lin H. and Mossberg, T. W., Presentation at the 1996 Annual Meeting of the Optical Society of America, session code WQ.
10. "Cavity enhancement of coherent transient signals;" Wang, T., Lin H. and Mossberg, T. W., Presentation at the 1996 Annual Meeting of the Optical Society of America, session code ThZZ5

Supported Personnel

1. Mr. Christoph Greiner, Graduate Research Assistant.
2. Mr. Bryan Boggs, Graduate Research Assistant.
3. Dr. Hai Lin, Ph.D. awarded through support from this AFOSR contract.
4. Dr. Tsaipei Wang, Ph.D. awarded through support from this AFOSR contract.
5. Prof. Thomas W. Mossberg, Principle Investigator

Ph. D. Dissertations

- "Study of the Power Efficiency of Coherent Transient Signals in Inhomogeneously Broadened Media," by Tsaipei Wang, University of Oregon (1999).
- "Response of Inhomogeneously Broadened Media to Frequency-Swept Optical Fields," by Hai Lin, University of Oregon (1996).

Invention

"Method and Apparatus for Laser Frequency Stabilization," T. W. Mossberg, C. Greiner, and B. Boggs, submitted to U. S. Patent Office 3/9/99, application No. 09,265,186. Priority of a Provisional Patent Application filed 3/9/98 is claimed. Notification of pending issue of all original claims has been received from the U. S. Patent Office.

Discussion

Spatial-spectral holographic techniques provide the potential for high speed, high density, storage of real time optical waveforms without electronic conversion - fully optical memory. Essentially the same process can be employed to implement real time processing (convolution, cross-correlation) of optical signals up to the high Gigahertz data regime. In order for the processes to be useful, it is highly desirable that operations be cascable and distributable. These processes require minimal insertion losses. For this reason, a successful effort was undertaken to identify those regimes in which spectral holographic devices could operate with minimal (and in fact sometimes negative) insertion loss.

Work on the energy efficiency and power of spatial-spectral holographic signals was focused on

simple photon and stimulated echo effects believed to be representative of behaviors to be expected in quite general situations. Two different scenarios were studied. In the first case, the generation of spatial-spectral holographic signals in single-pass media was considered. It was found that photon echo energy efficiencies, i. e. energy of output signal divided by energy of information-containing input signal, could exceed unity. In order to achieve this result, the material sample had to be chosen so as to be optically thick, i. e. in the absence of optical saturation, resonant power transport through the sample should fall in the e^{-3} or lower regime. Prior to the present work, it was believed by those working in the field that spatial-spectral holographic signals were optimized when sample absorption was on the order of $1/e$. The present results show optimization in a very different regime. It was also found that non-information containing input fields had to be chosen and configured to provide uniform excitation across the spectral bandwidth of the input signal and to provide specific degrees of sample excitation, i. e. specific input pulse areas. Finally, it was found that non-information-containing input pulses, having a spatial profile uniform across that of the input signal, are crucial in maximizing output signal intensity. A surprising result of the present work is that spatial-spectral output signals can actually be larger than input signals, i. e. the devices are capable of optical gain. In the application space, this attribute will be important as other problem areas involving frequency-selective recording materials (particularly related to necessary low material temperatures) are solved.

Another approach to obtaining large spatial-spectral signal sizes was explored. In this approach, a weakly absorbing sample is placed in a moderately high finesse cavity wherein the material absorption raised to a power equal to the cavity finesse was on the order of e^{-3} or lower. Use of the cavity approach allows one to use recording materials wherein intrinsic high absorptivity is not possible. It is found that the cavity method is effective in producing signal sizes that are comparable or even larger than those obtained in single-pass media. The cavity method of enhancing spatial-spectral signal size is also important in that the cavity acts as a power buildup device thereby lowering laser powers needed to effectively interact with the non-linear frequency-selective materials. Furthermore, in the cavity approach to spatial-spectral signal enhancement, the low intrinsic absorptivity of the recording material makes it

possible to subject it to uniform absorption along its length. Spatially uniform excitation makes it possible for more control over the processing functions implemented in device applications since they are often sensitive to the absolute power levels of the input signals involved.

The reported studies of spatial-spectral holographic energy efficiency in cavities have been the impetus to explore a broader set of questions in coherent light-matter interactions. Rare-earth atoms doped into inorganic crystals exhibit ultraslow decohering rates at cryogenic temperatures. In fact the decohering rates observed in cryogenic rare-earth doped systems are the smallest optical decohering rates ever observed in condensed phase materials. Recently, with the intense interest in quantum computing and related issues, it has become imperative to find and understand slowly decohering optical systems and to understand their radiative interactions. In the reported studies of spatial-spectral holographic signal size in cavities, it was necessary to construct a cavity system at cryogenic temperatures having a rare-earth-doped sample in its interior. The rare-earth-ion + cavity system is unique in that the ionic decohering rate sets the longest time-scale in the problem. Preliminary observations indicate unique new cavity-mediated light-matter interactions. Detailed study of these effects is being funded by a successor contract to the one being reported upon here.

Stable, yet frequency agile lasers were necessary to support the work described above. Such lasers are useful in multiple contexts and application areas many having nothing to do specifically with spatial-spectral holography. To perform the work reported here, development of stable, yet frequency agile lasers was necessary. To this end, a new and innovative method of cw laser stabilization was developed. In this method, sample laser output is split, one part is frequency shifted by an acousto-optic (AO) device, while the other part is delayed by several microseconds in optical fiber. The light is recombined producing a heterodyne beat signal. If the laser frequency is stable, the heterodyne beat frequency is simply the AO frequency offset introduced. On the other hand, if the laser is changing in frequency, the heterodyne frequency is the AO offset modified by an additive factor proportional to the time derivative of the laser's frequency. A phase-locked-loop is used to convert variations in heterodyne beat frequency to an error signal proportional to the laser frequency's time rate of change. The error

signal is then used to zero that rate and thereby lock the laser's frequency. The important point is that the laser frequency is stabilized without an external frequency reference. Moreover, the feed back circuitry can be configured to accept control inputs that provide for programmed excursions in laser frequency while the heterodyne feedback loop provides continuous elimination of unwanted FM noise. The unique character of the locking method has led to a patent application. The U. S. Patent office has already responded with a notification that the claims submitted have been allowed.

Application of spatial-spectral holographic processes has been constrained by the fact that intrinsically frequency-selective materials must be cooled to cryogenic temperatures in order to work. To avoid this problem, an effort was made under the auspices of the present contract to develop a radically new approach to implementing spatial-spectral holographic processes. The idea was to completely eliminate intrinsically frequency-selective materials from the picture. The effort was successful. As a replacement to intrinsically frequency-selective materials, the concept of a composite grating was developed. A composite grating is the overlay of multiple individual simple gratings each of which controls the spatial diffraction of light from a specific input direction to a specific output direction. By controlling the spatial phase and amplitude of the various subgratings relative to each other one can construct a composite grating structure with essentially an arbitrary spectral transfer function. This is precisely the underlying enabling feature of spatial-spectral holography. Composite surface gratings and composite fiber gratings have been demonstrated. In both cases, optical processing and waveform storage have been shown. Part of this work was in cooperation with an outside company, but the underlying concepts were developed at the University of Oregon under the present contract.

Composite fiber and surface gratings provide for the full implementation of spatial-spectral holographic concepts using highly robust and temperature insensitive materials, e. g. fused silica. The development of composite gratings promises to provide the pathway for spatial-spectral devices to pass the threshold of commercial viability to provide high bandwidth and economical optical signal processing, pattern recognition, and optical intelligence in a variety of formats including communications and computing.